A PARAMETRIC STUDY ON THE PULL-OUT RESPONSE OF SUCTION CAISSONS

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Abstract

Suction caisson foundation systems have been successfully used in the past two decades in numerous occasions on a variety of offshore structures in a wide range of environments. The pull-out capacity of suction caissons remains a critical issue in their applications, and reliable methods of predicting the capacity are required in order to produce effective designs. In the current study a numerical approach has been chosen to investigate the behavior of suction caissons under pull-out loads. The model has first been calibrated against available experimental data and also been verified against other test data. The verified model has then been used to study the influence of a number of parameters on the pull-out behavior of suction caissons. Variations in the soil type, soil cohesion, internal friction angle, dilatancy angle, Poisson's ratio and the aspect ratio of the caisson have been studied. Soil nonlinearities, soil/caisson interactions, drainage conditions and suction effects have also been taken into consideration. Simple approximations have been put forward to express the effects from above mentioned different parameters on the pull-out capacity. These approximations have also been compared with some analytical and simplified relationships proposed by other researchers.

Keywords: Suction Caisson, Pull-Out Capacity, Offshore Structures, Sand, Clay, Drained, Undrained, Aspect Ratio

Nomenclature

c:	Soil cohesion
φ:	Friction angle
ψ:	Dilatancy angle
S_u:	Undrained shear strength
D:	Caisson diameter
L:	Caisson length
L/D:	Aspect ratio
$R_{int.}$:	Soil/caisson strength reduction factor
P_u:	Ultimate pull-out load
$p_{u(net)}$:	Net ultimate pull-out stress under undrained conditions
$P_{u(net)}$:	Net ultimate pull-out load
P_{ud}:	Ultimate pull-out load under drained conditions
P_{uu}:	Ultimate pull-out load under undrained conditions
q:	Pull-out stress capacity
	$q_{u(net)}$: Net ultimate pull-out stress under drained conditions
$\sigma_v^{'}$:	Effective vertical stress
δ_{ud}:	Displacement at ultimate load under drained conditions
δ_{uu}:	Displacement at ultimate load under undrained conditions

1.Introduction

Suction caissons are hollow steel (or concrete) cylinders which are open at bottom but capped on their top (Fig.1). They are allowed to penetrate the seafloor under their own weight and then pushed to the required depth with differential pressure applied by pumping water out of the caisson.

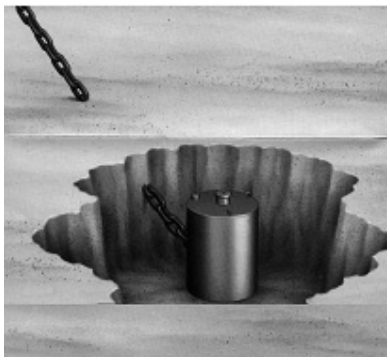


Fig.1- Schematic view of a suction anchor pile [1]

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Suction caissons have been employed to a greater extent as foundations for deep-water offshore structures and anchors for mooring lines. Depending on their applications and dimensions, they are also called suction cans, suction piles, bucket foundations, suction anchors or skirted foundations. Their incipient goes back to late sixties, but investigations on their behavior virtually commenced late eighties. They are considered as a solution for marine shallow foundations and are an attractive option with regard to providing anchorage for floating structures in deep water as they offer a number of advantages in that environment. Suction caissons are easier to install than impact driven piles and can be used in water depths well beyond where pile driving becomes infeasible. Suction caissons have higher load capacities than drag embedment anchors and can be inserted reliably at pre-selected locations and depths with minimum disturbance to the seafloor environment and adjacent facilities [2].

One crucial aspect for a suction caisson is its capacity to resist pull-out loads which commonly arise under harsh environments to which they are usually exposed. This has been investigated by some researchers using experimental and analytical approaches [3, 4, 5, 6, 7, 8, 9, 10, 11]. Suction caisson's pull-out behavior has also been studied by means of numerical simulations, involving extensive axisymmetric and three-dimensional models. For example Sukumaran et al. [12], Erbrich and Tjelta [13], El-Gharbawy and Olson [14], Deng and Carter [15] and Maniar et al. [16] carried out studies to determine suction caissons capacity under different loading and drainage conditions. The commercial finite element codes ABAQUS, PLAXIS, CRISP3D and other codes such as AFENA have been used by these researchers.

It should be noticed that suction caissons are relatively new as compared to piled foundations, which benefit from more than a century of experimental, analytical and computational investigation on their behavior. Reliable rules for describing the behavior of suction caissons are yet subject to development and investigation. The effects from different parameters such as the caisson geometry, soil characteristics, soil/caisson interaction nature on the load bearing capacities of suction caissons still need further attentions. The current numerical study mainly deals with effects from a number of above mentioned parameters into the behavior of suction caissons subjected to vertical pull-out loads. It has been tried to make a distinction between different types of the pull-out responses and the tendency each parameter affects the pull-out capacity. These aspects appear to have been overlooked in previous numerical studies (for example [12 to 16]).

2.Numerical models of the caisson

Modeling of nonlinear and time dependent responses of soils requires advanced numerical programs. The two dimensional finite element program PLAXIS [17] has been used to model the pull-out behaviour of suction caissons.

The saturated soil has been modeled as a two-phase medium composed of solid (soil skeleton) and pore-fluid (water) phases. Nonlinear behavior of the solid phase is described by means of a Mohr-Coulomb elasto-plastic model. This involves five input parameters, i.e. Young's modulus (E) and Poisson's ratio (ν) for soil elasticity, internal friction angle (φ) and cohesion value (c) for soil plasticity and angle of dilatancy (ψ). The Mohr-Coulomb yield condition is an extension of Coulomb friction law to general states of stress. In fact, this

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condition ensures that Coulomb's friction law is followed in any plane within a material element. The full Mohr-Coulomb yield condition can be defined by three yield functions when formulated in terms of principal stresses [18]. The yield functions together represent a hexagonal cone in principal stresses. In addition to the yield functions, three plastic potential functions are also defined for the Mohr-Coulomb model.

The employed soil plastic model is versatile but relatively simple. As will be reported later, this plastic criterion has proved to yield to an acceptable level of correspondence between the numerical results and experiments available on suction caissons. The program offers some complicated plastic models but they require more detailed soil data which was not made available with those experiments used for the verifications/calibrations of the numerical models.

A two dimensional axisymmetric finite element model has been used. Six-node triangular elements which provide a second order interpolation for displacement have been considered. The element stiffness matrix is evaluated by numerical integration using a total of three Gauss points (stress points). The caisson itself has been modeled by non-porous linear elastic materials with elastic modulus which correspond to their material properties.

A key feature with geotechnical models containing structural elements is the type and formulations used for the interaction between the soil and structural elements. Special interface elements in PLAXIS take care of soil/structure interactions. Interface elements with three pairs of nodes have been employed to simulate the soil/structure interaction. They are consistent with the six-node soil elements for the soil body. An interface strength reduction factor (R_{int}) in PLAXIS characterizes the elastic-plastic modeling of soil/structure interactions.

A standard fixity boundary condition has been considered on the soil boundaries of the model. The pull-out load has been introduced on top of the caisson and above its walls to avoid possible flexural deformations from structural elements used for the caisson cap. In the vicinity of the caisson a relatively fine meshing has been used for the soil body while, coarser meshes have been utilized elsewhere to reduce computational efforts (Fig.2). A load advancement number of steps option, which better suits those cases where a failure load is expected during the analysis, has been used. The water level has been considered to be around 1-3L above the soil surface. It should be mentioned that the results have not been found to be affected by the water level height.

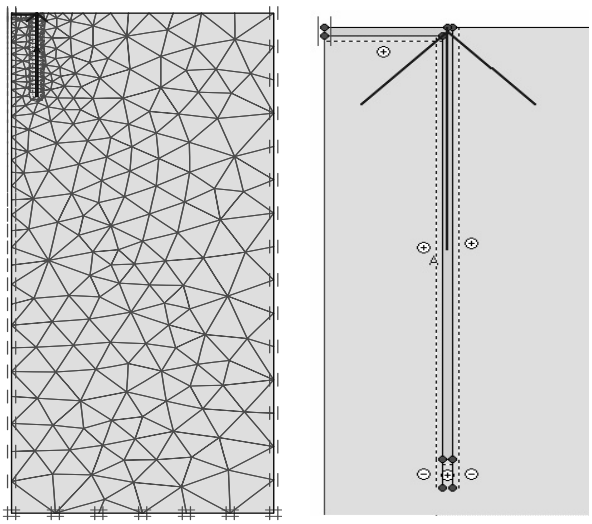


Fig.2- A view from one of the numerical models (left), magnified view of the caisson and the pull-out load (right)

In the current investigation, the suction caisson is assumed being already installed in soils and that it has regained its original intact strengths which was prevailing in the soils prior to the installation of the caisson. In other words, the soil properties are primarily

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assumed to be unaffected by the caisson installation. This assumption, however, remains to be verified by experiments.

With drained conditions no excess pore pressure is generated. This is obviously the case where free drainage has been allowed through the top cap of the caisson. An undrained condition allows for full development of excess pore pressure and is used when, during the pull-out, the top cap remains closed.

Numerical models, employed in the current study, have been initially validated against experimental records available in the literature. The laboratory data used for the calibration/verification of numerical models are those from Rao *et al.* [19], El-Gharbawy and Olson [6] and Iskander *et al*. [10].

Rao *et al.* [19] carried out a series of tests on suction caissons with different aspect ratios (L/D) to get an estimate of their pull-out capacity in soft clays (similar to those in the Indian waters). The caisson dimensions in their experiments were:

$D = 75\ mm \quad t = 3\ mm \quad L/D$=1.0, 1.5 and 2.0

El-Gharbawy and Olson [6] conducted pull-out tests on caisson models with different aspect ratios (2 to 12) in kaolin clays under drained and undrained conditions. They tried to evaluate the response of suction caisson foundations for TLPs in the Gulf of Mexico in deep waters of 2000 to 3000m. The caisson dimensions in their tests were:

$D = 100\ mm \quad t = 3.125\ mm \quad L/D = 4$ and 6

Iskander *et al.* [10] performed tests in sands to investigate the variation of the pore pressure during the penetration and subsequent pull-out of the suction caisson models. Oklahoma sand, which is quite fine and of round corners, has been used in their experiments. The caisson dimensions in their tests were:

$L = 194\ mm \quad D = 110\ mm \quad t = 5\ mm$

In Fig.3 experimental results from El-Gharbawy and Olson [6], as an example, have been compared with corresponding numerical results from the current study. The figure depicts load-displacement response for a caisson model in clay with aspect ratios of 6 under drained conditions. Relatively good agreement can be noticed between numerical and experimental responses. In general, the examined numerical models have shown an acceptable level of correspondence with test results from above referenced experiments for other soil types and drainage conditions.

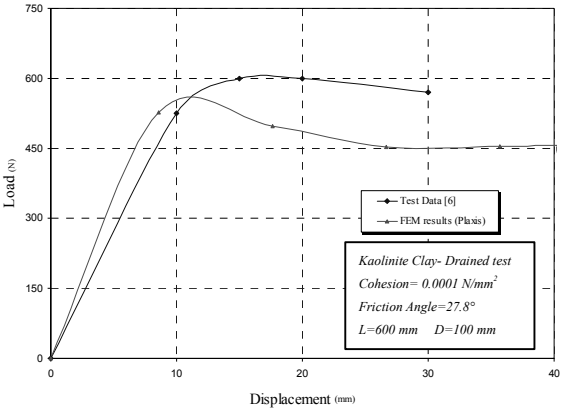


Fig.3- Comparison between the experimental (from El-Gharbawy and Olson; [6]) and numerical (current study) results for suction caissons, diameter of 100mm in soft marine clay under drained conditions.

Based on the mentioned verification attempts, it has been concluded that employed numerical models are convincingly able to predict the response of suction caissons in different soil types and drainage conditions with acceptable accuracies.

3.Effect of different soil/ caisson parameters on the pull-out capacity

Effects from different caisson/soil/drainage conditions on the pull-out behavior of suction caissons have been investigated. The utilized

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numerical models in the current study are, in general, based on dimensions of the experimental models used by El-Gharbawy and Olson [6] for clays and Iskander *et al.* [10] for sands respectively. As previously stated, these test data have also been used for the verification of the FE models.

3.1.Ultimate Pull-Out Capacity

In general, four distinctive pull-out load-displacement responses have been identified. Fig.4 outlines how the pull-out capacity P_u has been defined with suction caissons performing post-ultimate softening and or hardening, respectively. Displacement limits, as recommended by Rao et al. [19], have also been taken into consideration for determining the ultimate pull out capacity (Fig.4).

3.2.Basic Scenarios and Parameters Studied

Parametric studies have been performed in four basic scenarios each relating to a specific caisson/soil/drainage configuration. They are suction caissons:

- in *clay* under *drained* conditions
- in *clay* under *undrained* conditions
- in *sand* under *drained* conditions
- in *sand* under *undrained* conditions

The numerical model, in each of above scenarios, simulates in particular one test in the previously referenced experiments. For each parametric study, all parameters in the numerical model have been kept constant while one parameter in soil/caisson properties has been changed. Key parameters which their effects on the pull-out capacity have been examined are:

- soil cohesion (c)
- soil internal frication angle (φ)
- soil dilatancy angle (ψ)
- soil Poisson's ratio (v)
- interface strength reduction factor (R_{int})
- caisson's aspect ratio (L/D), while D is constant but L varies
- caisson's aspect ratio (L/D), while L is constant but D varies.

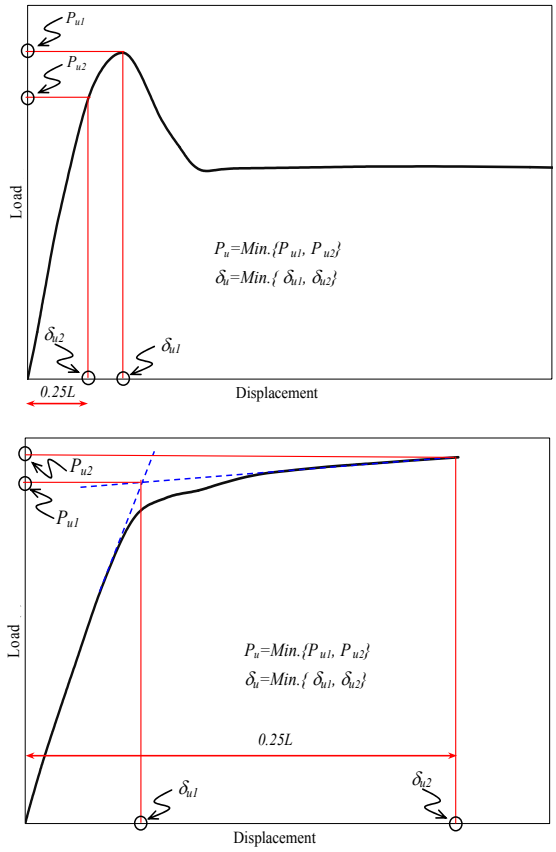


Fig.4- Pull-out capacity with suction caissons performing post ultimate softening behavior (top) and post ultimate hardening behavior (bottom), as defined in the current study.

3.3. Soil Cohesion Effect

3.3.1. General Results

Cohesion is the resistance due to the forces tending to hold the particles together in a solid mass [20]. Cohesion has important effects on the behavior of structures embedded in the soil (particularly in clays). Soil cohesion also appears to influence the pull-out response of suction caissons.

In numerical models identical to that of experiments in clays [6], the cohesion value (c) has been changed from 0.0001

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to 0.03 N/mm^2, to verify its effect. Other soil/caisson parameters in the model have been kept constant. Both drained and undrained conditions have been considered (scenarios No. 1 and 2). Some of the results are given in Figs.5 to 7.

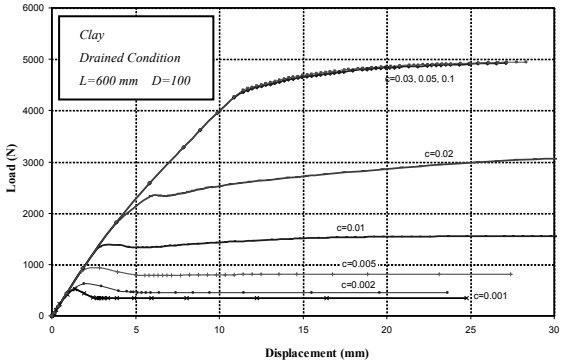


Fig.5- Soil cohesion effects on numerical pull-out responses of suction caissons in clay under drained conditions.

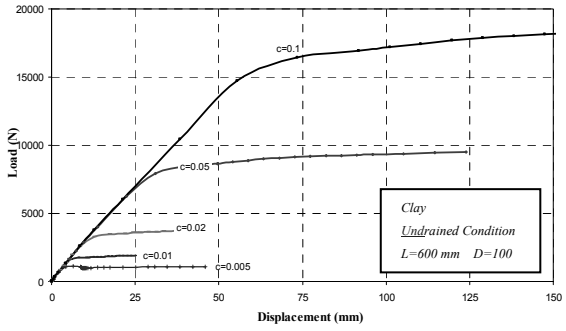


Fig.6- Soil cohesion effects on numerical pull-out responses of suction caissons in clay under undrained conditions

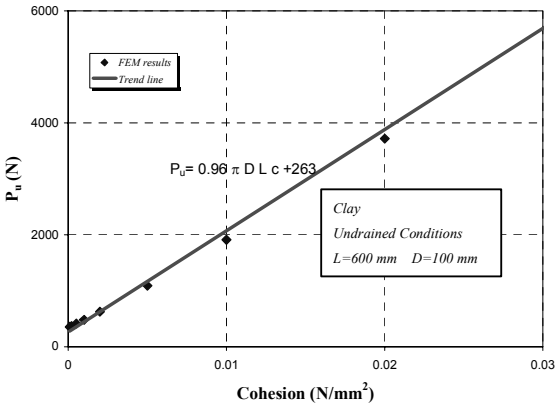


Fig.7- Soil cohesion effects on pull-out capacity of suction caissons in clay under undrained conditions.

Results obtained indicate that under both drained (scenario No. 1) and undrained (scenario No. 2) conditions, the ultimate pull-out load (P_u) almost linearly increases with the increase in (c) values (for example see Fig.7). A linear trend between ultimate pull-out load (P_u) and cohesion (c) is not far from anticipated. This is because the shear strength over the caisson skin and in the soil body both are directly related to the soil cohesion. Linear semi-empirical relationships between the soil undrained shear strength and the pull-out stress capacity was also proposed by other researchers [21]:

$$q = 6.42 S_u \left[1 + 0.18 \tan^{-1}\left(\frac{D}{L}\right)\right] \quad (1)$$

and under drained conditions [15]:

$$q_{u(net)} = \left[9.48\left(\frac{L}{D}\right)^{-0.18} + 3.792\left(\frac{L}{D}\right)^{+0.82}\right] S_{u(tip)} \quad (2)$$

or under undrained conditions [15]:

$$p_{u(net)} = 9.1\left(\frac{L}{d}\right)^{0.537} (1-\sin\phi')(OCR)^{\sin\phi'} \tan\phi' \sigma'_{v(bottom)} \quad (3)$$

3.3.2. Review of the Results

Under drained conditions, the pull-out capacity P_u was noticed to increase by an increase in the soil cohesion. However, high values of soil cohesion did not have extra improving effect on the pull-out capacity.

Further review of the results indicated that, under drained conditions the failure was mostly local (developed either on the caisson walls or in the soil plug). Undrained conditions, however, mostly resulted in a post failure hardening response and their failure surfaces were extended in the surrounding soils far from the caisson.

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Generally speaking, Figs.5 and 6 show that the pull-out capacities under undrained conditions are considerably higher than those from corresponding models under drained conditions ($P_{uu} >> P_{ud}$). This difference is partially due to a change in the mode of failure for undrained suction caissons compared to that for drained caissons. Besides, the suction developed inside undrained caisson directly contributes to the load bearing capacity. The suction, moreover, results in improvement of the soil resistance characteristics in the vicinity of the caisson and indirectly augments the pull-out capacity.

From Figs.5 and 6 it can also be recognized that, under undrained conditions the caisson displacement at failure point δ_u is notably higher than that under the corresponding drained conditions ($\delta_{uu} >> \delta_{ud}$). This is also believed to be due to a shift in the failure mechanisms of the caisson (from weak local modes under drained conditions towards demanding global modes under undrained conditions). These higher displacements required to achieve the ultimate capacity point out on wider margins of safety for undrained caissons.

It is necessary to mention that in here a drained condition corresponds to pull-out cases when openings in the caisson top cap allow free drainage. An undrained condition refers to pull-out cases when the top cap remains closed and the pull-out has a high loading rate.

A linear equation shown in Fig.7 relates the pull-out capacity (P_u) to the soil cohesion (c) and has been found to best fit the numerical results obtained in the current study. Similar relationships have been obtained under drained conditions. These equations are in the form of:

$$P_u = \alpha_1 \pi D L c + B_1 \qquad (4)$$

Values of α_1 and B_1 are 0.96 and 263 N respectively for studied undrained models and 0.82 and 147 N under drained conditions. It should be emphasized that this paper is mainly aimed to evaluate the significance of different soil/caisson parameters on the pull-out capacity. Eq. 4 and similar forthcoming equations just provide indications on the order and the tendency that a specific parameter influences the pull-out capacity. Delivering a comprehensive analytical solution for the pull-out capacity of suction caissons is out of the scope of this paper.

In general, the pull-out capacity of a suction caisson (P_u) comprises components from the submerged weight of the caisson, its surcharge, the submerged weight of the soil plug, the negative pressure (suction) developed inside the caisson (just under undrained conditions), frictional shear strength on the caisson outer and inner skins and the reverse end bearing.

The constant part in Eq. 4 (B_1) can be related to the submerged weight of the caisson, the submerged weight of the soil plug, the negative pressure and other parameters which remain typically unchanged with variations in soil cohesion (such as the skin friction that is originated from the soil internal friction angle). Under drained conditions, suction effects are vanished and the constant part (B_1) grows smaller than that of undrained models. It has also been noticed that in weak soils under drained conditions, the soil plug does not accompany the caisson up to the failure point. It means that in these cases the weight of the soil plug will not contribute to the constant part (B_1).

The variable part in Eq. 4 (α_1) is associated with the soil cohesion effect on the pull-out capacity of the caisson. Interior and exterior skin area surfaces of the caisson contribute to α_1. It was

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noticed that with some models failure occurs just on the outer skin. With some models it happens on both the inner and the outer skins and in some on a conic wedge around the caisson [22]. Coefficient α_1 therefore has to represent the ratio between the actual failure surfaces to the caisson wall skin surface. Coefficient α_1 is also related to the ratio of the soil/caisson interaction (R_{int}).

Greater values for α_1 have been obtained under undrained conditions as compared with those from corresponding drained conditions. This is most likely caused by the failure surface shifting from the caisson's vicinity (under drained conditions) to more extended areas in the surrounding soil (under undrained conditions). In the latter case, development of suction ensures reductions in the positive pore pressure. It creates higher effective stresses in the soil body and greater normal stresses on failure surfaces. Consequently higher shear and frictional forces are accumulated over the failure surfaces. Negative pressures also prevent a premature tensile failure in the soil plug [22]. Therefore under undrained conditions, both α_1 and B_1 show higher values than their respective drained models.

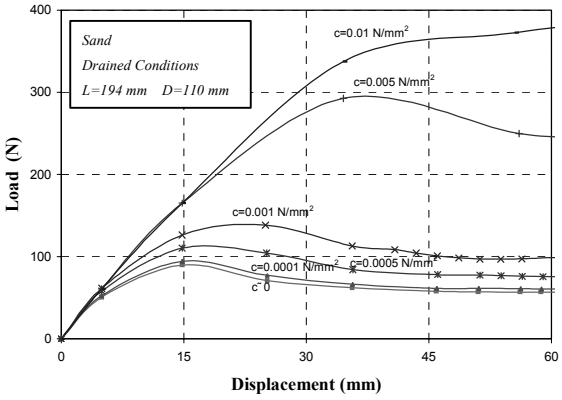


Fig.8- Soil cohesion effects on numerical pull-out responses of suction caissons in sand under drained conditions.

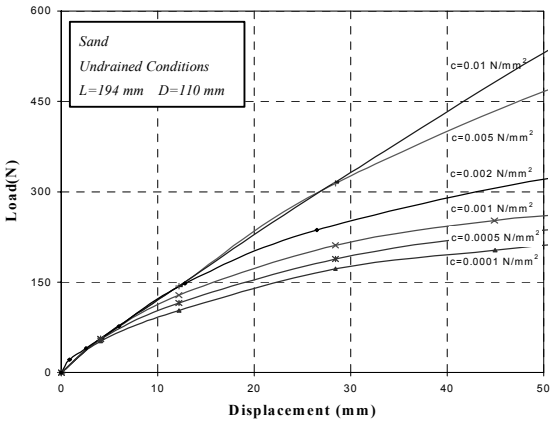


Fig.9- Soil cohesion effects on numerical pull-out responses of suction caissons in sand under undrained conditions.

For models in sand (scenarios No. 3 and 4) a more limited range has been considered for the soil cohesion (from almost zero to 0.01 N/mm^2). Results from sand models are given in Figs8 and 9. They virtually demonstrate the same linear trend observed with models in clay, for the cohesion effects on the pull-out capacity. Values of α_1 and B_1 are 0.48 and 238 N respectively for undrained models while they are 0.44 and 106 N for drained models. Therefore α_1 presents smaller values compared to the clay models. This is somehow due to lesser interface ratios (R_{int}) considered for sand models than that of clay models (0.4 compared to 0.5 respectively). Smaller penetration of studied sand models, compared to that of clay models, have been noticed to generally result in lesser pull-out capacities.

3.4.Soil Internal Friction Angle Effect

3.4.1.General Results

The internal friction angle (φ) is the resistance due to interlocking of the particles [20]. It is another key factor influencing the pull-out capacity of suction caissons. Effects from variations of φ values on the pull-out capacity have

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been examined within the four already mentioned basic scenarios.

Numerical models employed in the study are identical to that of experiments in clays (from El-Gharbawy and Olson [6]), and in sands (from Iskander *et al.* [10]). All soil/caisson parameters in the reference models have been kept constant while φ values change in a range of 10 to 35 degrees for clays and 20 to 41 degrees for sands. It is acknowledged that some of these values are far from actual field conditions but have been introduced into the models to allow for a more extend range of parameters.

Some of the results are shown in Figs.10 to 12. These figures demonstrate that the ultimate pull-out capacity of suction caisson models monotically increases with an increase in φ values. An exponential relationship has been presented which provide a good correlation between φ values and the obtained numerical P_u values. They are in the form of:

$$P_u = P'_o e^{\alpha_2 \varphi} \tag{5}$$

Values obtained for P'_o and α_2 are summarized in Table 1. P'_o and α_2 vary in different scenarios depending on the soil type and the drainage conditions.

Besides, a linear equation in terms of tan(φ). which seems to be of better physical meaning, fits the obtained numerical

$$P_u = \alpha_3 \frac{\pi \gamma' D L^2}{2} \tan(\varphi) + P''_o \tag{6}$$

Values observed for α_3 and P''_o in basic scenarios are summarized in Table 1.

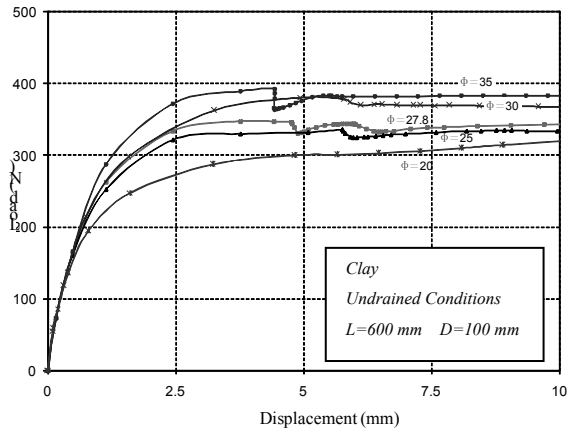


Fig.10- Soil friction angle effects on numerical pull-out responses of suction caissons in clay under undrained conditions.

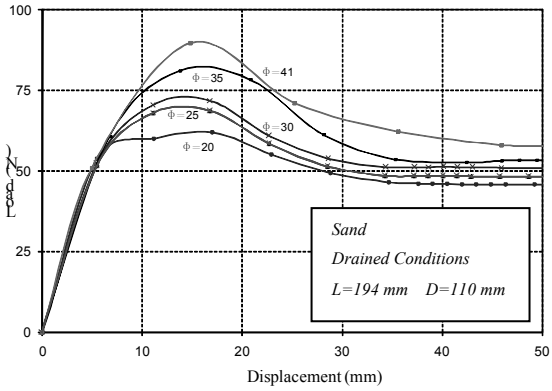


Fig.11- Soil friction angle effects on numerical pull-out responses of suction caissons in sand under drained conditions.

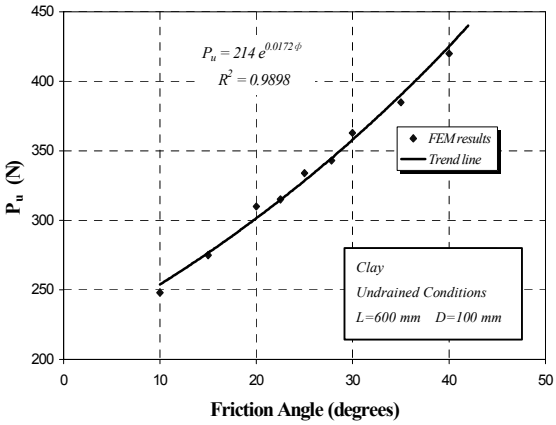


Fig.12- Soil friction angle effects on pull-out capacity of suction caissons in clay under undrained conditions.

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Table 1- Variations of coefficients in Eqs. 5 and 6 in different analysis scenarios.

Scenario No.	Condition	α_2	P'_o (N)	α_3	P''_o (N)
1	Clay-drained	0.0213	195	0.83	186
2	Clay-undrained	0.0172	214	0.68	209
3	Sand-drained	0.0178	44	0.80	43
4	Sand-undrained	0.0131	120	1.32	124

3.4.2.Review of the Results

In general, models studied under undrained conditions achieve pull out capacities greater than those from corresponding drained models. This is seemingly owing to development of suction, negative pore pressures and hydraulic gradients under undrained conditions. They bring about higher effective stresses which magnifies the soil friction angle effects. The drainage conditions become more pronounced with models in sand. This is obviously a result of higher permeability in sand models which allows for further extension of the suction through the soil body.

Drained responses in Fig.8 and 11 typically demonstrate a load drop ahead of their ultimate pull-out load P_u (a post ultimate softening response). This softening response is mostly believed to be caused by a local failure either in shear on the caisson vertical skins or in tension at the interface of the soil plug with the soil underneath the caisson tips [22]. Subsequent to the drop, the pull-out load remains almost constant. This residual strength emerges from the soil plug and the caisson submerged weights and the plastic resistance on the caisson skins.

On the other hand, undrained models (despite those of low penetration) do not show the above mentioned load drop or softening (see for example Fig.9). Beyond P_u (see Fig.4) the pull-out load keeps increasing with increase in the displacement (a post ultimate hardening response). This is most likely because with undrained models, even beyond failure, suction still keeps on its improving effects on the load bearing characteristics of the system. Within post failure region, as the pull-out advances up, yet extra suction is produced inside the caisson. This directly augments the load bearing of the caisson.

The suction also indirectly improves the soil resistance on failure surfaces. Upon development of a plastic state in elements and as the pull-out proceeds further, extra suctions are created. This results in an increase in effective stresses in the soil body around the caisson and in normal stresses acting on failure surfaces. Consequently the yield surfaces grow bigger. It means that although the element stresses remain in a plastic state, as the normal stresses increase, higher shear strength are developed over the yield surfaces. Therefore with undrained models, beyond the ultimate load, the direct and indirect effects of the suction provide a mounting load bearing response or a hardening behavior (Fig.9). The slope of the load-displacement curve in the post failure region (the hardening rate) is generally less than the slope prior to P_u (see for example Figs.4 and 9). The reason is that in the post failure region, in contrary to the pre-failure zone, only the suction effect contributes to the load bearing of the soil.

It has been noticed that with clay models the post ultimate hardening rate, although still positive, is much lower than that from sand models. This is likely because lower permeability in the clay restricts the suction effect in comparison to that from sand models. Failure modes observed in undrained clay models are closer to the caisson body while they become more extended in the sand models.

Under undrained conditions, failure modes noticed to be global, in shear and in the soil body surrounding the caisson.

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They are dissimilar to failure modes with drained models (and models of low penetration) where failure modes observed to be local and happening on the caisson walls or in the soil plug [22].
Yet again in undrained models the caisson's upward displacement at the failure point (δ_u) has been found to be notably higher than that of the corresponding drained model ($\delta_{uu} >> \delta_{ud}$). Suction's direct effects (negative pressure) and indirect effects (seepage forces, change in the pore pressure in the soil and increase in the effective stress) seem to postpone the caisson failure to higher levels of deformations. Pertaining to the caisson safety, high deformations at the limit point load and the hardening type response in the post ultimate region, both observed with the undrained models, provide better load bearing behaviors.

3.5.Dilatancy Angle Effect

Dilatancy angle represent positive plastic volumetric strain increments as actually observed for dense soils. Its effect has only been examined with scenarios No. 3 and 4. Clays, apart from over consolidated ones, do not perform dilatancy behavior [23]. Dilatancy angle of sand depends on its relative density and degree of interlocking. For quartz sands it can be expressed by:

$$\psi = \phi - 30^{\circ}$$

In most cases, where φ is less than 30^{o}, ψ can be considered as zero. Small values of ψ are acceptable for loose sands with low relative densities [23].
Results obtained indicate that under drained conditions, the pull-out capacity of suction caissons virtually exhibits no changes with variations in ψ angle. With undrained models, an almost linear upsurge in the pull-out capacity has been noticed in respect to ψ tangent. For higher ψ values, improved post failure behavior has been recognized for the suction caissons under both drained and undrained conditions. This is because in the numerical program the dilatancy angle (ψ) introduced in the plastic potential functions besides the yielding Mohr-Coulomb functions. They are in the form of:

$$\begin{aligned} g_1 &= \frac{1}{2}\left|\sigma_2' - \sigma_3'\right| + \frac{1}{2}\left|\sigma_2' + \sigma_3'\right|\sin\psi \\ g_2 &= \frac{1}{2}\left|\sigma_3' - \sigma_1'\right| + \frac{1}{2}\left|\sigma_3' + \sigma_1'\right|\sin\psi \\ g_3 &= \frac{1}{2}\left|\sigma_1' - \sigma_2'\right| + \frac{1}{2}\left|\sigma_1' + \sigma_2'\right|\sin\psi \end{aligned} \qquad (7)$$

It means that the dilatancy angle introduces its effects mostly in the plastic regions of the behavior. It was previously discussed that with drained models a post failure softening response (or in their best performance a residual strength equal to their ultimate capacity) has been observed. It means that these caissons reach their ultimate capacity prior to when dilatancy angle starts to effectively function. This is most probably why drained models have not shown changes in their pull-out capacity (as a result of change in the dilatancy angle). Undrained models, on the other hand, show post failure hardening responses. Consequently, both the pull-out capacity and the post failure responses can be affected by the variations in the dilatancy angle.

3.6.Poisson's Ratio Effect

With all four basic scenarios, variations of Poisson's ratio show almost insignificant effects on the load bearing capacities of suction caissons. The reason is that the ultimate pull-out capacity of suction caissons is usually achieved far away from their elastic performance, where the Poisson ratio may impose its foremost effects.

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3.7.Interface Strength Ratio Effect

Interface strength reduction factor or Rint indicates the portion of the cohesion and friction strength from the soil (in the vicinity of caisson skins) that can be transferred to the caisson when subjected to the pull-out. Effects from variations in R_{int} have been examined in four previously mentioned basic scenarios. Results obtained indicate almost a linear relationship between the ultimate pull-out loads P_u and R_{int}. This relationship can be expressed in the form of:

$$P_u = \alpha_4 \pi D L R_{\text{int}} + B_4 \qquad (8)$$

It can be concluded that an increase in the interaction between the soil and the caisson, such as provisions proposed by Dendani [24] for vertical inserts to the caisson wall, can most possibly result in improvement of the pull-out capacity. However this extra interaction will have some negative impacts on the installation of the suction caisson.

3.8.Aspect Ratio (*L*/*D*) Effects

This parameter has been studied in the already mentioned four basic scenarios but in two different instances. In the first instance, D is kept constant while the aspect ratio varies and in the second instance, L remains constant while the aspect ratio changes.

3.8.1.While (*D*) Remains Constant

Figs.13 to 15 present some of the results obtained from four basic numerical scenarios. They reveal considerable improvements in the pull-out capacities by the increase in the aspect ratios. Two types of trendlines have been examined which both fit properly the numerical results. The first series in the form of:

$$P_u = P_o''' \ (L/D)^m \qquad (9)$$

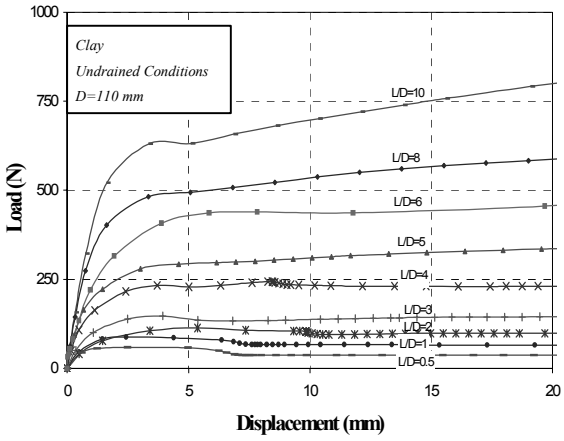


Fig.13- Aspect ratio effects (*D* remains constant) on numerical pull-out responses of suction caissons in clay under undrained conditions.

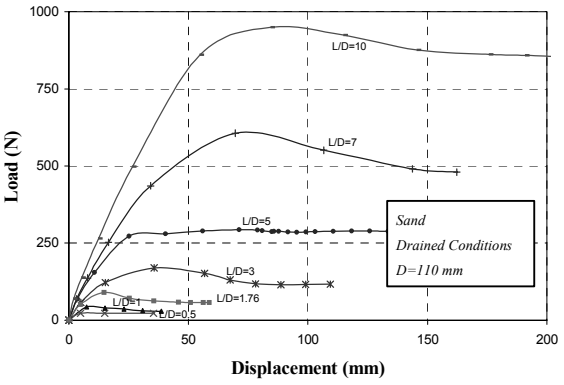


Fig.14- Aspect ratio effects (*D* remains constant) on numerical pull-out responses of suction caissons in sand under drained conditions.

Higher values of P_o''' have been observed under undrained conditions compared to those of drained conditions, but the power m shows a slight decrease. The changes have noticed to be more substantial in sand models in comparison to the clay models (Table 2).

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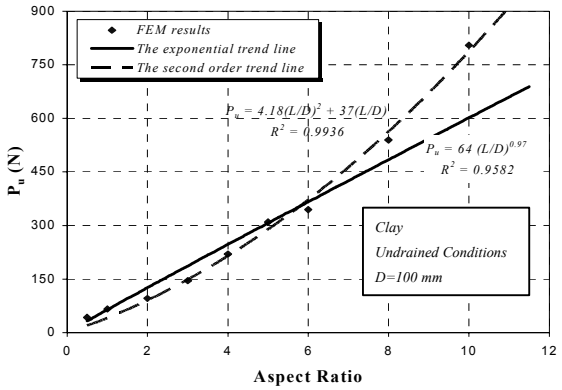


Fig.15- Aspect ratio effects (*D* remains constant) on pull-out capacity of suction caissons in clay under undrained conditions.

Other researchers considered similar trends between the caisson aspect ratio and the net ultimate pull-out stress of the caisson. For example Rahman *et al.* [8] presented these equations:

- Under drained conditions:

$$q_{u(net)} = 8S_{u(tip)}\left(\frac{L}{D}\right)^{-0.11833}\left(1+0.4\tan^{-1}\left(\frac{L}{D}\right)\right)+\gamma' L \qquad (10)$$

- Under undrained conditions:

$$p_{u(net)} = 9.1\left(\frac{L}{d}\right)^{0.5372}(1-\sin\phi')(OCR)^{0.5}\tan\phi'\sigma'_{v(bottom)} \qquad (11)$$

Lengthening of the caisson (increase in the aspect ratio while *D* remains constant) leads to more voluminous caisson, heavier soil plug and accordingly higher weights. It also increases the contact surface between the soil and caisson and consequently increases the friction forces developed over their interfaces. Lengthening of the caisson also increases the average normal forces acting on the caisson wall skins. In addition, it increases the drainage path, boosts seepage forces and improves the suction effect on the load bearing of the caisson.

Another form of equation is proposed in the current study, which relates the pull-out capacity to the aspect ratios as follows:

$$P_u = A_2(L/D)^2 + B_2(L/D) \qquad (12)$$

Values of A_2 and B_2 in four basic scenarios are summarized in Table 2. Eq. 12 seems to be of better physical interpretation. The pull-out resistance is partially originated from components being directly and linearly related to the caisson length (*L*) such as submerged weights of the caisson wall, submerged weight of the soil plug, soil cohesion effects, etc. There are also components acting with the second orders of the caisson's length such as soil internal friction angle effects. The latter can be assumed as the product of the normal stresses acting on the caisson's skins which are themselves depth dependant, and the caisson's wall surface areas. They are both directly related to the caisson length and therefore justify a second order effect from the caisson's depth.

3.8.2.While (*L*) Remains Constant

When the caisson length (*L*) remains constant, a decrease in the caisson aspect ratio (*L*/*D*), indicates a larger diameter (*D*), a bulkier and heavier caisson, a more stocky soil plug and increased interface areas between the soil and the caisson. As the aspect ratio decreases, the above mentioned parameters create higher frictional and cohesive resistances on the interface areas and consequently a higher total pull-out capacity is achieved.

With all four basic scenarios, the ultimate pull-out capacity has been found to increase with the decrease in the aspect ratio of the caisson. Some of

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the results are given in Figs.16 and 17. With the studied cases some relationships, between the pull-out capacity and the aspect ratio, have been derived (see also Fig.18):

$$P_u = P_o''''(L/D)^{-n} \quad (13)$$

Under both drainage conditions, Eq. 13 marks a general improvement of the pull-out capacity with decrease in the aspect ratio. However the changes become more pronounced when the aspect ratio moves further below 1. With undrained models, P_o'''' and n demonstrate higher values compared to those from drained models. It means that, in this instance, undrained models show more sensitivity to the change in the aspect ratio as compared with that of the drained models.

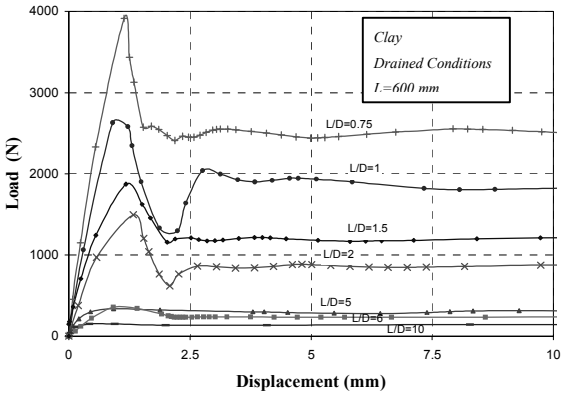


Fig.16- Aspect ratio effects (*L* remains constant) on numerical pull-out responses of suction caissons in clay under drained conditions (models are based on test data from El-Gharbawy and Olson [6])

Table 2- Variations of coefficients of Eqs. 9, 12 and 13 in different analysis scenarios.

Scenario No.	Condition	P_o''' (*N*)	*m*	A_2 (N)	B_2 (N)	P_o'''' (*N*)	*n*
1	Clay drained	49	1.21	0.77	55	2800	1.23
2	Clay undrained	64	0.97	4.18	37	10100	1.70
3	Sand drained	47	1.25	5.63	40	140	1.25
4	Sand undrained	169	0.72	1.62	97	470	1.56

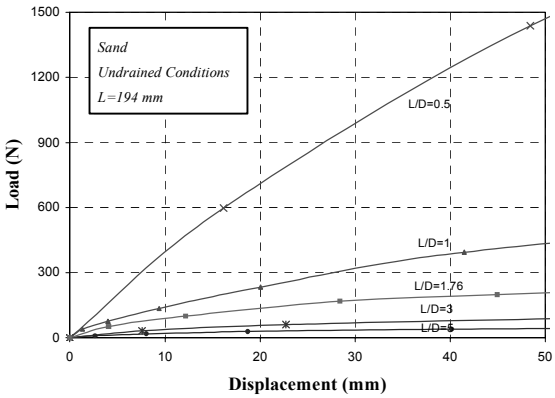


Fig.17- Aspect ratio effects (*L* remains constant) on numerical pull-out responses of suction caissons in sand under undrained conditions (models are based on test data from Iskander *et al.* [10]).

Coefficients obtained in Eqs. 9 and 12 (and 13) for studied models in different scenarios are summarized in Table 2.

As it was already mentioned, presenting wide-ranging relationships for the pull-out capacity of suction caissons is out of the scope of this paper. This paper mainly deals with the order and the trend that a specific parameter in soil/caisson/drainage condition influences the pull-out capacity. However, and in general, the previously discussed relationships and parameters may be arranged in an overall form of:

$$P_{u(net)} = \pi D L^2 R_{\text{int}} (\alpha \gamma' \tan(\varphi) + \beta \frac{c}{L} + \delta \gamma' (\frac{D}{L})) \quad (14)$$

where $P_{u(net)}$ is the ultimate pull out load of the caisson excluding its self weight. Coefficients α, β, and δ depend on soil/caisson/drainage conditions. Eq. 14, its range of validity, effects from soil/caisson/drainage conditions on its parameters, its correlation with the experimental and numerical results and other related issues will appear in a separate paper.

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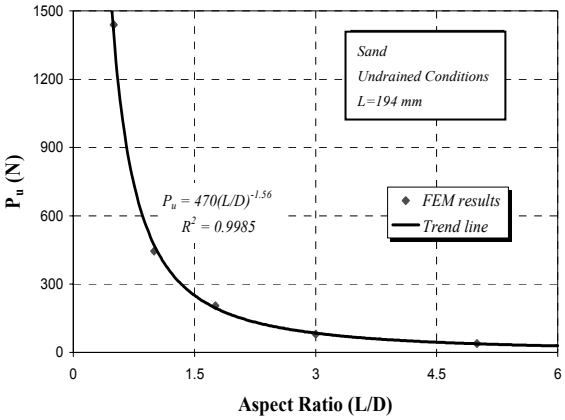


Fig.18- Aspect ratio effects (*L* remains constant) on pull-out capacity of suction caissons in sand under undrained conditions.

4.Conclusions

A numerical approach has been chosen in the current study to investigate effects from different soil/caisson/ drainage conditions and parameters on the pull-out behavior of suction caissons. The numerical models have been found to present an acceptable level of correspondence to available experimental data from other researchers.

Based on the numerical results, a linear relationship has been observed between soil cohesion values and the pull-out capacity. The soil internal friction angle has been noticed to have an exponential increasing effect on the pull-out capacity. Poisson's ratio and the dilatancy angles have been understood to have no significant effects on the pull-out strength. With constant values of the caisson diameter, an increase in the aspect ratio noticed to have a second order effect on the friction originated part and a linear influence on the cohesion originated part of the resistance. With constant values of the caisson length, an increase in the aspect ratio values has been found to result in an exponential decrease of the pull-out capacity.

Simple formulations and approximations have been proposed in order to estimate the effects of the studied parameters on the pull-out capacities. The approximations have also been compared with some analytical and simplified equations already been proposed in the literature for evaluation of the caisson pull-out capacities.

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